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PARAMETRIC LIMITS FOR THE UPPER ATMOSPHERE OF MARS

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PREFACE

This Memorandum provides physical data useful for the development of engineering design criteria for space vehicles grazing or entering the upper atmosphere of Mars. It represents an extension of earlier work, notably P-2639, Engineering Model Atmosphere of Mars, to higher altitudes into the aerodynamic flight regime of orbiting satellites and lifting entry vehicles. The work was performed under Contract AF 49(638)-700.

ABSTRACT

Probable upper and lower limits are here calculated for the distribution of atmospheric pressure and mass density in the upper atmosphere of Mars. The results extend an earlier engineering model atmosphere from an altitude of 150 km to one in excess of 2500 km above the planetary surface. They derive, in part, from a recent analysis by J. W. Chamberlain of the probable thermal regime in the upper atmosphere of planets, while taking into account our present uncertainties about the lower atmosphere of Mars.

The three self-consistent model atmospheres (Tentative Maximum, Tentative Minimum, and Tentative Standard) should bracket actual conditions in the Martian atmosphere up to 500 km altitude and, above that, plausibly represent the extreme range of probable conditions. At any specific altitude level, the true daily mean values prevailing during any season over middle and low latitudes should fall between these limits. If no specific season, time of day, or latitude is specified, the Tentative Standard Atmosphere will estimate in orders of magnitude for the whole altitude range those pressures and densities that will probably occur more often than not. The parametric limits presented here are, however, only two of an infinity of choices permitted by presently available factual knowledge.

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CONTENTS

I. INTRODUCTION

The AFOSR-GE Symposium on Dynamics of Manned Lifting Planetary Entry in October, 1962, demonstrated that the very high regions of planetary atmospheres were important for the system design of certain types of advanced space vehicles. The aerodynamicist and design engineer were demanding data that the astrophysicist and meteorologist were reluctant to supply because of the almost complete lack of factual information.[1] Recent policy announcements indicate[2] that Mars will probably be the first goal of manned interplanetary flight, and that serious studies towards this objective are in progress.[3] An attempt seems warranted, therefore, to provide the basic physical data for the development of engineering design criteria for vehicles grazing or entering the Martian upper atmosphere.

In previous studies,[4] the author has used whatever factual information was available to derive limiting model atmospheres of Mars and to develop an engineering model atmosphere[1] up to an altitude of 150 km above the surface. Wegener,[5] for example, has used some of these scientific data to describe the aerodynamic flight regimes of Mars, but has pointed out that, even at altitudes of 200 km, the atmosphere is aerodynamically dense and that a flight vehicle would still encounter the continuum regime. On the other hand, Vachon[6] has illustrated by numerical examples the well-known fact that straight mathematical extrapolation of low-altitude data to altitudes above a few hundred kilometers will, with the assumption of an exponential atmosphere, lead to very serious misconceptions about the physical state of any planet's upper atmosphere.

Finally, one must remember that we are still uncertain about the upper atmosphere of our own planet. Only since the advent of artificial satellites, have we begun to get reliable quantitative information about the large variations of temperature, pressure, and density which occur in the Earth's upper atmosphere as a function of solar activity,[7] time of day,[8] and season.[9] Nevertheless, the following sections describe a method for extending the probable limits of Mars' basic atmospheric parameters to altitudes in excess of 2500 km. The author,

knowing how speculative his method is, cautions the reader that the tabulated parametric limits may be seriously in error; in fact, they may be utterly wrong at altitudes above 500 km. Hopefully, observations of Mars by unmanned space probes or from earth-based high-altitude balloons should soon give us some answers.

II. METHOD OF APPROACH

An earlier work[4] emphasized the scarcity of "factual," numerically reliable data on the Martian atmosphere. To avoid relying on subjective "best" values, that work used optimization methods resulting in model atmospheres that constituted probable-extreme limits for the basic atmospheric parameters up to some 150 km in altitude. Actual conditions over middle and low latitudes on Mars, regardless of time of day or season, could then be expected to fall within these limits.

A number of studies are now available in the recent literature, e.g., the excellent work by Zimmerman and Jones[10] and Wegener,[5] using similar approaches to convert the astronomical and atmospheric data for Mars into parameters for engineering and the description of flight regimes. But, as mentioned, an extrapolation of such quantities to higher altitudes cannot be made mathematically alone; it must take into account a wide variety of complex but possible physical processes in the upper atmosphere of a planet.

This Memorandum will use extensively the deductive model of the upper atmosphere of Mars developed by Chamberlain.[11] His basic ideas about radiative processes in the Martian thermosphere were combined with ours concerning optimization; the results yielded a reasonable extension of the earlier engineering model atmosphere[1] to altitudes beyond 2500 km.

In brief, our reasoning was thus: Chamberlain analyzes the probable consequences of the absorption of ionizing and dissociating far-ultraviolet solar radiation in the Martian thermosphere above the mesopause. He derives the probable conductive heat flux through the upper atmosphere and, through an iterative technique, bases the properties of the thermosphere (the region where the temperature begins to increase with altitude due to solar energy absorption through photo-ionization and photodissociation) on the properties of the mesopause. In consequence,

he has to locate the mesopause arbitrarily at an altitude where a number of complex conditions may be fulfilled--specifically at a density value where the conductive heat flux is completely radiated away, but where the temperature is quite uncertain.

We now argue that far-ultraviolet solar radiation will penetrate from above the atmosphere down to a certain depth, i.e., the level of the mesopause, independent of the pressure and density structure of the atmosphere below this level. The penetration depth will depend on the amount of atmospheric mass above the mesopause, and the absorption characteristics in the thermosphere, i.e., the molecular and atomic composition. Further, Bates[12] has shown that rates of gain and loss of thermal energy in a planetary thermosphere are rather insensitive to the temperature and influenced only indirectly through the atmospheric density. Barth[13] has pointed out that the composition of the upper atmosphere of Mars may be similar to that of Earth in that nitrogen will be the major component responsible for radiation effects at high altitudes. This is borne out by Chamberlain's quantitative data (see Ref. 11, Fig. 2).

To specify the probable range of altitudes for the Martian mesopause, we use Chamberlain's discussion of thermal heat flux to determine the amount of mass penetrated by solar far-ultraviolet radiation down to the mesopause. The exact altitude above the planetary surface will critically depend on assumptions made both about the values of atmospheric parameters near the surface of Mars and about their vertical distributions in the troposphere and mesosphere. But regardless of any initial starting values, the atmospheric pressure at the mesopause will be unaffected by the temperature distribution above it, and Chamberlain's conditions for the location of the mesopause will be fulfilled somewhere in the Martian atmosphere. From our limiting model atmospheres[4] we can find not only the altitudes where these conditions are fulfilled for upper (as well as lower) extreme limits, but also the temperatures associated with these levels.

Once the Martian mesopause has thus been located for both upper and lower limiting conditions, these limits could theoretically be extended upward through the thermosphere and exosphere to interplanetary

space. But the energy state of a planetary atmosphere has a variety of well-known complications.(14,15) For convenience, studies of the Earth's upper atmosphere have divided it on the basis of those complications that are most significant in terms of thermal state and behavior. Likewise, plausible assumptions and restrictions can be made by so treating the Martian upper atmosphere.

The Appendix gives a more detailed discussion of the applied concepts and mathematical details. From various assumptions, we were able to extend the altitude variation of atmospheric parameters up to 2600 km above the planetary surface, getting both upper and lower probable limits even at these high altitudes.

III. PARAMETRIC RESULTS

Numerically applying the concepts described in the Appendix produced a series of model atmospheres for Mars, each self-consistent and physically valid for a particular configuration of planetary and atmospheric data. Since the objective was to derive upper- and lower-probable limits for the variation of pressure and density in the upper atmosphere of Mars, three models that reasonably fulfill this requirement were selected and labelled as follows:

TENTATIVE MAXIMUM — probable upper limit,

TENTATIVE STANDARD — probable average,

TENTATIVE MINIMUM — probable lower limit.

The principal characteristics of these model atmospheres are illustrated in Figs. 1, 2 and 3, and are summarized below. Values of atmospheric pressure and density from the planetary surface to 2800 km altitude are tabulated in Table 1. A more detailed discussion is found in Appendix D, and Table 6 gives the construction parameters while Table 7 gives the thermal regimes with an example of a representative molecular mass distribution.

TENTATIVE MAXIMUM

This model atmosphere represents extreme conditions that may be encountered if the lower portion of a dense Martian atmosphere is heated with maximum efficiency by absorption of solar radiation in both the troposphere and the mesosphere. The mesopause level is found at an altitude of about 215 km and at a temperature of some 85^{o}K. At higher altitudes, the atmosphere is again absorbing solar energy with high efficiency, causing dissociation of the constituent gases. It is assumed — for this extreme case — that the molecular scale temperature could reach 4400^{o}K at an altitude of 2700 km. This high molecular scale temperature would correspond to a kinetic temperature ranging from 1100^{o} with a mean molecular mass of 7 (e.g., ionization as well as complete dissociation, and helium, hydrogen, or oxygen the dominant species) to 4400^{o}K (without any dissociation).

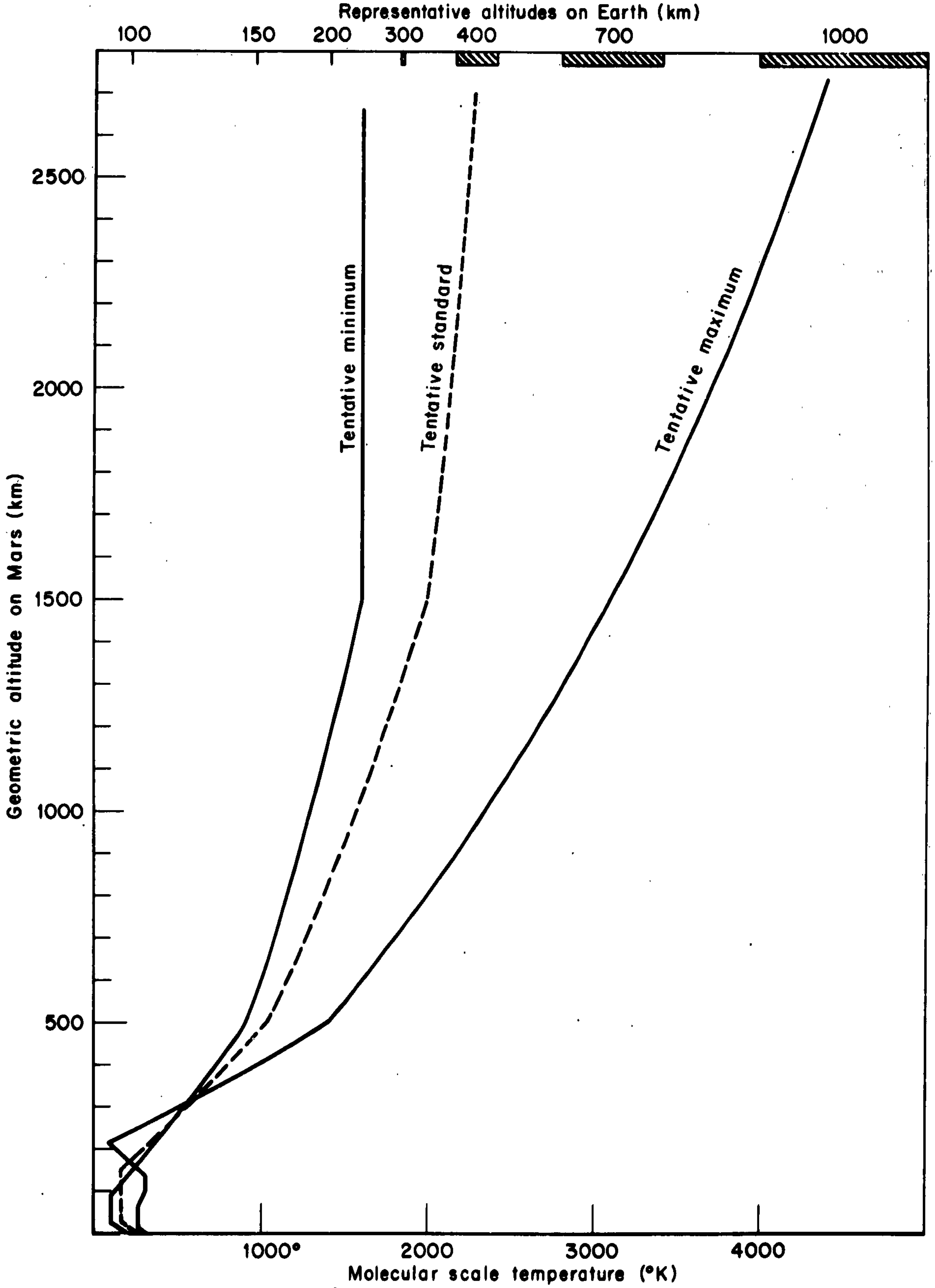

Fig. 1 — Variation of molecular scale temperature with altitude for tentative model atmospheres of Mars

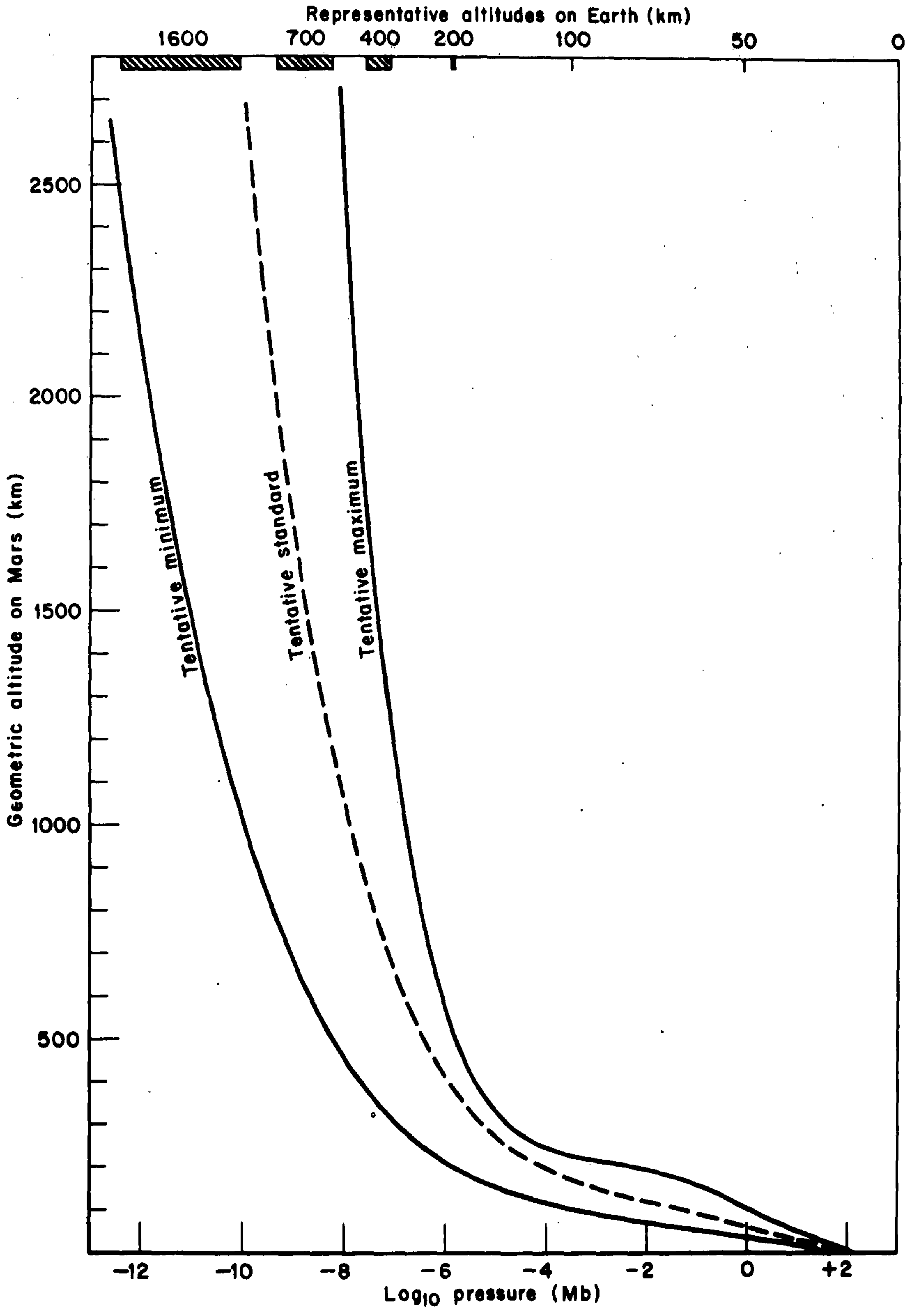

Fig.2 — Variation of atmospheric pressure with altitude for tentative model atmospheres of Mars

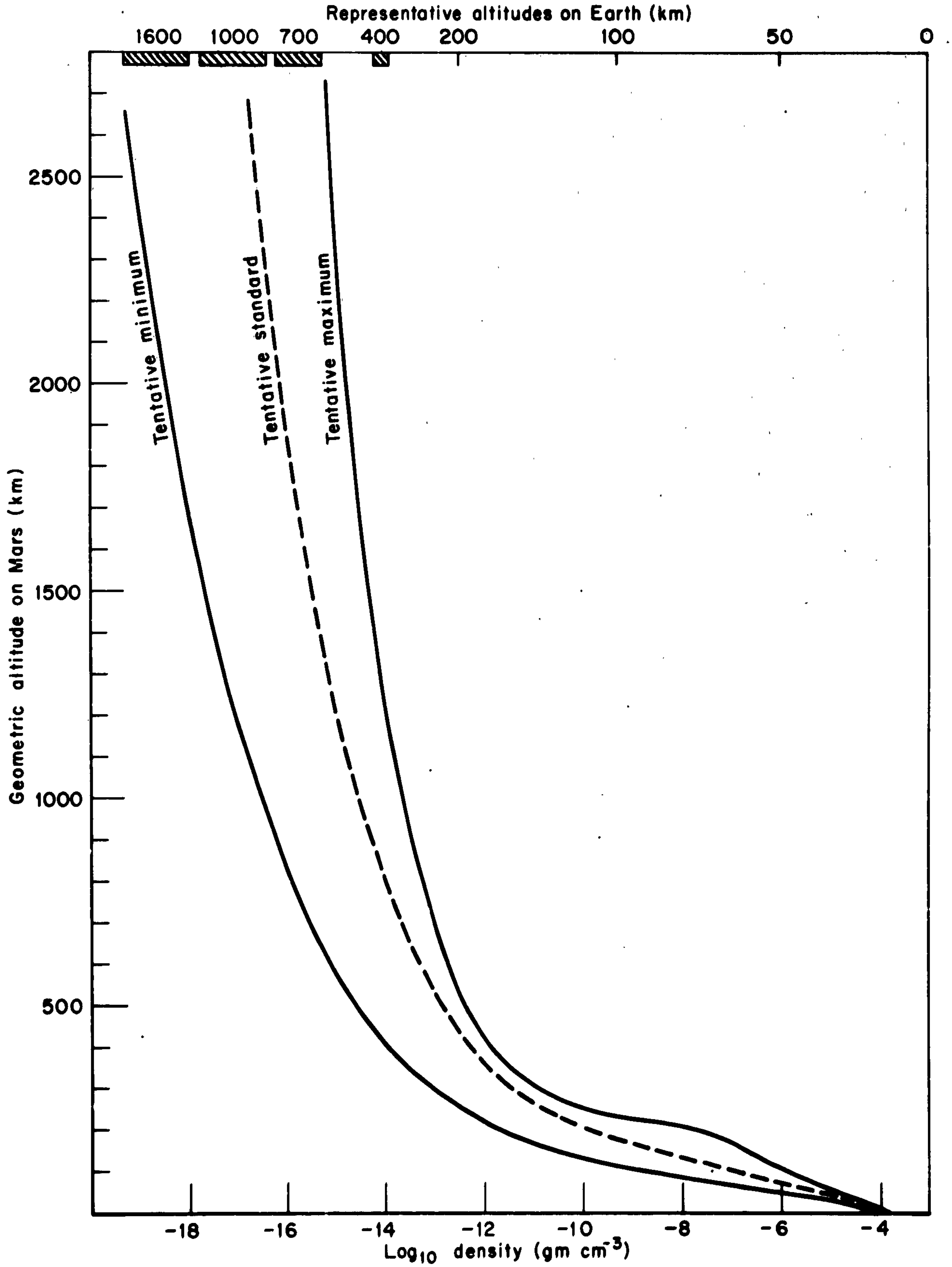

Fig.3 — Variation of atmospheric density with altitude for tentative model atmospheres of Mars

Table 1

TENTATIVE MODEL ATMOSPHERES

Geometric Altitude (km)	Atmospheric Pressure (mb)			Atmospheric Density (gm cm^{-3})		
	MINIMUM	STANDARD	MAXIMUM	MINIMUM	STANDARD	MAXIMUM
0	4.10×10^{1}	8.50×10^{1}	1.33×10^{2}	7.40×10^{-5}	1.19×10^{-4}	1.49×10^{-4}
2	3.59×10^{1}	7.64×10^{1}	1.21×10^{2}	6.74×10^{-5}	1.10×10^{-4}	1.40×10^{-4}
4	3.13×10^{1}	6.85×10^{1}	1.11×10^{2}	6.11×10^{-5}	1.02×10^{-4}	1.31×10^{-4}
6	2.71×10^{1}	6.12×10^{1}	1.01×10^{2}	5.52×10^{-5}	9.38×10^{-5}	1.22×10^{-4}
8	2.34×10^{1}	5.44×10^{1}	9.17×10^{1}	4.97×10^{-5}	8.63×10^{-5}	1.14×10^{-4}
10	2.00×10^{1}	4.82×10^{1}	8.31×10^{1}	4.45×10^{-5}	7.91×10^{-5}	1.06×10^{-4}
20.1	8.02×10^{0}	2.51×10^{1}	5.04×10^{1}	2.33×10^{-5}	4.66×10^{-5}	6.46×10^{-5}
30.3	2.40×10^{0}	1.18×10^{1}	3.06×10^{1}	8.54×10^{-6}	2.54×10^{-5}	3.92×10^{-5}
40.5	6.68×10^{-1}	5.30×10^{0}	1.86×10^{1}	2.37×10^{-6}	1.14×10^{-5}	2.38×10^{-5}
50.7	1.86×10^{-1}	2.37×10^{0}	1.13×10^{1}	6.60×10^{-7}	5.08×10^{-6}	1.44×10^{-5}
60.0	5.86×10^{-2}	1.15×10^{0}	7.18×10^{0}	2.09×10^{-7}	2.47×10^{-6}	9.20×10^{-6}

Table 1 (Continued)

Geometric Altitude (km)	Atmospheric Pressure (mb)			Atmospheric Density ($gm\ cm^{-3}$)		
	MINIMUM	STANDARD	MAXIMUM	MINIMUM	STANDARD	MAXIMUM
70.4	1.63×10^{-2}	5.2×10^{-1}	4.37×10^{0}	5.80×10^{-8}	1.10×10^{-6}	5.51×10^{-6}
79.8	5.15×10^{-3}	2.49×10^{-1}	2.83×10^{0}	1.83×10^{-8}	5.34×10^{-7}	3.45×10^{-6}
90.3	1.43×10^{-3}	1.11×10^{-1}	1.78×10^{0}	5.09×10^{-9}	2.39×10^{-7}	2.08×10^{-6}
100	4.9×10^{-4}	5.4×10^{-2}	1.2×10^{0}	1.48×10^{-9}	1.15×10^{-7}	1.34×10^{-6}
120	8.5×10^{-5}	1.2×10^{-2}	5.2×10^{-1}	1.9×10^{-10}	2.5×10^{-8}	5.8×10^{-7}
140	2.3×10^{-5}	2.7×10^{-3}	2.3×10^{-1}	4.0×10^{-11}	5.8×10^{-9}	2.7×10^{-7}
160	8.1×10^{-6}	6.3×10^{-4}	9.0×10^{-2}	1.2×10^{-11}	1.2×10^{-9}	1.3×10^{-7}
180	3.4×10^{-6}	2.1×10^{-4}	2.8×10^{-2}	4.2×10^{-12}	2.9×10^{-10}	5.3×10^{-8}
200	1.6×10^{-6}	9.0×10^{-5}	5.8×10^{-3}	1.7×10^{-12}	1.0×10^{-10}	1.6×10^{-8}
250	3.6×10^{-7}	1.8×10^{-5}	8.6×10^{-5}	3.0×10^{-13}	1.4×10^{-11}	1.1×10^{-10}
300	1.1×10^{-7}	5.6×10^{-6}	1.8×10^{-5}	7.6×10^{-14}	3.5×10^{-12}	1.2×10^{-11}
400	2.0×10^{-8}	3.0×10^{-6}	4.0×10^{-6}	1.0×10^{-14}	5.0×10^{-13}	1.4×10^{-12}

Table 1 (Continued)

Geometric Altitude (km)	Atmospheric Pressure (mb)			Atmospheric Density (gm cm^{-3})		
	MINIMUM	STANDARD	MAXIMUM	MINIMUM	STANDARD	MAXIMUM
500	5.8×10^{-9}	3.7×10^{-7}	1.6×10^{-6}	2.3×10^{-15}	1.3×10^{-13}	4.0×10^{-13}
600	2.0×10^{-9}	1.5×10^{-7}	8.5×10^{-7}	7.5×10^{-16}	4.5×10^{-14}	1.8×10^{-13}
700	9.0×10^{-10}	7.0×10^{-8}	5.0×10^{-7}	3.0×10^{-16}	2.0×10^{-14}	9.0×10^{-14}
800	4.0×10^{-10}	3.7×10^{-8}	3.2×10^{-7}	1.2×10^{-16}	9.4×10^{-15}	5.4×10^{-14}
900	1.9×10^{-10}	2.1×10^{-8}	2.1×10^{-7}	5.6×10^{-17}	4.8×10^{-15}	3.3×10^{-14}
1000	1.0×10^{-10}	1.2×10^{-8}	1.5×10^{-7}	2.9×10^{-17}	2.7×10^{-15}	2.1×10^{-14}
1200	3.4×10^{-11}	5.0×10^{-9}	8.2×10^{-8}	8.6×10^{-18}	9.9×10^{-16}	1.0×10^{-14}
1400	1.4×10^{-11}	2.4×10^{-9}	5.1×10^{-8}	3.2×10^{-18}	4.3×10^{-16}	5.8×10^{-15}
1600	6.1×10^{-12}	1.3×10^{-9}	3.4×10^{-8}	1.4×10^{-18}	2.2×10^{-16}	3.5×10^{-15}
1800	2.9×10^{-12}	7.1×10^{-10}	2.4×10^{-8}	6.6×10^{-19}	1.2×10^{-16}	2.3×10^{-15}
2000	1.5×10^{-12}	4.3×10^{-10}	1.8×10^{-8}	3.4×10^{-19}	7.0×10^{-17}	1.6×10^{-15}
2200	8.0×10^{-13}	2.7×10^{-10}	1.4×10^{-8}	1.8×10^{-19}	4.3×10^{-17}	1.2×10^{-15}

Table 1 (Continued)

Geometric Altitude (km)	Atmospheric Pressure (mb)			Atmospheric Density (gm cm^{-3})		
	MINIMUM	STANDARD	MAXIMUM	MINIMUM	STANDARD	MAXIMUM
2400	4.5×10^{-13}	1.8×10^{-10}	1.1×10^{-8}	1.0×10^{-19}	2.7×10^{-17}	9.0×10^{-16}
2600	2.6×10^{-13}	1.2×10^{-10}	8.9×10^{-9}	5.9×10^{-20}	1.9×10^{-17}	7.0×10^{-16}
2700	2.0×10^{-13}	1.0×10^{-10}	8.0×10^{-9}	5.0×10^{-20}	1.5×10^{-17}	6.2×10^{-16}

This model atmosphere, in terms of the altitude variation of pressure and mass density, might be found on a Martian summer day in equatorial latitudes during perihelion. The critical level of escape is to be found at extremely high altitudes, in excess of 2500 km. Thus, the noticeable atmosphere reaches much farther from the planetary surface than it does on Earth.

TENTATIVE MINIMUM

This model atmosphere is valid for extreme conditions of a cold, thin Martian atmosphere. The mesopause level is located near 91 km altitude at a temperature of about 101°K. A gradual rise in molecular scale-temperature leads to values of 906°K near 500 km, and 1600°K near 1500 km. The escape level is between 590 km and 635 km at a molecular-scale temperature of 985°K to 1020°K. This corresponds to an approximate kinetic temperature of 900°K with dissociation to a molecular weight of 26 or 27, or to one of 1000°K without any appreciable dissociation. It might be found on a Martian winter night in middle latitudes near aphelion.

TENTATIVE STANDARD

This model atmosphere was selected as being representative of Martian conditions thought to average by most authors. The mesopause occurs at an altitude of 144 km with a temperature of 162.5°K. The molecular scale temperature rises gradually to 1990°K near 1500 km and continues to increase to almost 2300°K at approximately 2700 km. From above 1500 km the true kinetic temperature probably remains almost constant near 1100°K, the molecular scale-temperature rising because of molecular dissociation, with consequent decrease of the mean molecular mass to values of 14 near 2600 km.

Depending on the precise variation of gravitational acceleration with altitude, primarily the latitude concerned, the critical level of escape is between 1540 km and 1760 km. The molecular scale-temperature there is between 2000°K and 2070°K, e.g., corresponding to a mean molecular weight of 15.7 for a kinetic temperature of 1100°K.

This Tentative Standard Model Atmosphere probably represents no actual conditions found on Mars at any one time, place, or altitude. But it should indicate the approximate values of pressure and temperature likely under conditions averaged over day, season, latitude, and orbit position. As with model atmospheres for Earth,[9,16] its primary use will be for preliminary engineering designs.

GENERAL APPLICATION

These tentative model atmospheres will be useful if their purposes are kept in mind. The Tentative Maximum and Tentative Minimum models will give valid numerical limits for values of atmospheric pressure and mass density at altitudes ranging from 0 km to some 2500 km. At any specific altitude, the true values prevailing at any time or season over middle and low latitudes should fall between these limits. The Tentative Standard Atmosphere, on the other hand, will give those order-of-magnitude estimates of pressure and density for the whole altitude range — estimates that will be close to reality more often than not, if no specific season, time of day, or latitude is specified.

IV. DISCUSSION

The numerical data can only be as reliable as the many assumptions that preceded the computation. Unfortunately, there is not enough factual information available to assess in any way their reliability or probability. Nevertheless, the method used here will probably be less in error than any straight extrapolation of lower-altitude values from an isothermal upper atmosphere without dissociation, i.e., based on an exponential variation of density with altitude above the mesopause. This is so, however, only because the assumption of a constant-temperature/molecular-mass regime is untenable from the point of view of planetary physics, and would lead to the maximum possible errors in high-altitude densities.

In essence, this analysis extends that of Chamberlain[11] to allow for our uncertainties concerning the lower atmosphere of Mars. In addition, little is said here about the molecular and atomic constituents of the Martian thermosphere and exosphere above some 500 km. Earlier work by Yanow[17] indicated how complex are the processes which may occur in this region and lead to ionized layers analogous to the Earth's ionosphere. Rasool[18] recently criticized Chamberlain's analysis of the Martian ionosphere for having an escape-level kinetic temperature so low (1100°K) that it could not allow for diurnal variations nor for increases associated with solar activity; hence, its electron-density distribution might be an upper limit. Rasool does not offer an alternative approach, however, beyond pointing out that temperature variations in the Earth's upper atmosphere are known to be possibly as high at 500°K as a function of local time and solar activity. Nor does Rasool seem to have considered the role of diffusive equilibrium at these altitudes,[19] a role that tends to fortify Chamberlain's numerical results.

Further critical analysis of the exosphere raises questions as to how far from the surface does the atmosphere continue to rotate with the planet as a solid.[20] Though the answer to this question depends upon the magnitude of a Martian magnetic field and upon its interaction with solar wind, the present study implicitly assumed that the Martian atmosphere does rotate with the planet up to the altitudes considered.

V. CONCLUSIONS

An infinity of self-consistent model atmospheres of Mars could be constructed from presently available factual knowledge. Though the parametric limits presented here are just two from this infinity, they are probably rather reliable for altitudes from the surface up to some 500 km. Between 500 km and 1500 km, they plausibly represent the range of probable conditions. For still higher altitudes, the upward extension at a constant exospheric temperature (kinetic) can presently be considered only as a best guess. This does imply, in essence, that the Martian exosphere is at an altitude of 1500 km or more.

The tentative model atmospheres show that despite the planet's smaller volume and mass, the sensible atmosphere extends to proportionally much higher altitudes than on Earth. This anomaly is caused by the atmospheric dissipation rate's depending not on the gravitational acceleration, but on the gravitational potential; it is the latter that determines the critical escape-velocity of the atoms and molecules, as well as the altitude variations of pressure and density. This must always be remembered when trying to "compare" the physical characteristics of different planetary atmospheres at various geometric altitudes above the surfaces.

Numerical comparison with Earth,[16] for example, immediately demonstrates that artificial satellites will experience considerably higher drag effects while orbiting Mars than at similar altitudes above the Earth's surface. To show this, Figs. 1, 2, and 3 contain an upper scale of representative Earth altitudes for each parameter. These Earth scales are based on the U. S. 1962 Standard Atmosphere[16] below 400 km. Above this altitude, they are based on satellite drag data and reflect the variations of temperature, pressure, and density as a function of local time and solar activity in the Earth's upper atmosphere. In terms of the planetary gravitational fields, on the other hand, a geometric altitude of 2700 km on Mars corresponds to one of about 630 km on Earth; and we find, for example, that atmospheric pressures on both planets have dropped to about 10^{-12} of their respective surface pressures at this radial distance. The

density scale-height is a governing parameter for planetary entry. For meaningful comparison with Earth, however, we must consider it in terms not of geometric-altitude intervals but of the relative decrease of atmospheric density over corresponding differences of gravitational potential surfaces.

Finally, as with any standard atmosphere,[16,21] it is well to remember that the values falling between the envelope curves of any of the parameters could not possibly be encountered at all altitudes at any given location and time. In other words, the maximum spread is not representative of actual variability at any altitude, but merely provides for extreme conditions that could exist somewhere over nearly the entire globe of Mars. At no time is it likely that the atmosphere will assume the lower (or upper) limit distribution throughout its depth, or through any major segment thereof.

On Earth, for instance, the warmest surface layers in the tropics are known to be associated with the coldest (and highest) tropopause levels. In Fig. 1, the temperature envelopes indicate the possibility of an analogous phenomenon — the Martian mesopause — governing the vertical distribution of atmospheric density. But any specific altitude distribution of atmospheric parameters throughout the atmosphere within the permissible ranges will also evidence this characteristic. Hence we have difficulty, without better observational data, in providing physically significant <u>mean</u> or standard altitude distributions, or in narrowing the parametric limits.

In fact, very recent spectroscopic observations have led Kaplan[22] to conclude tentatively that the surface pressure on Mars may be as low as 20 mb. Such an atmosphere, probably consisting mostly of CO_2 and argon, would fall outside of even the lower probable limits derived here. This is a further illustration, if we needed one, that present factual knowledge does not permit us to specify any degrees of probability to the present work.

Appendix A

MATHEMATICAL TECHNIQUE

A program has been developed for the IBM 7090 Computing Machine, which rigorously evaluates the hydrostatic equation under the assumption that the atmosphere behaves as an ideal gas. While this procedure would be trivial for an exponentially decreasing atmosphere in an inverse-square, central gravitational field, an actual planetary atmosphere such as Mars' requires a solution that takes into account the empirical data we have as well as that which we lack. This we can achieve by so designing the computing program as to permit substitution of known, composite variables for unknown data at any altitude level with explicit requirements for necessary assumptions.

Let the perfect gas law be:

$$p = \frac{\rho R^{*} T}{m} = n k T \quad , \tag{1}$$

where

p = atmospheric pressure (in dynes cm^{-2}),
ρ = mass density (in g cm^{-3}),
T = true kinetic temperature (in ^{o}K),
m = mean molecular mass,
n = number density of particles (per cm^{3})
R^{*} = universal gas constant, and
k = Boltzmann constant,

where the hydrostatic equation to be integrated is

$$dp = - g_{(z)} \rho_{(z)} dz \tag{2}$$

where

$g_{(z)}$ = gravitational acceleration at altitude z (in cm sec^{-2}) and
z = geometric altitude above MSL or mean planetary surface (in cm).

The integration to obtain p and ρ at any altitude z can be performed through substitution for the variables z, T, and m as detailed below.

POTENTIAL HEIGHT

A potential height h is defined as

$$h = \frac{\Phi_o - \Phi_z}{g_o} = \frac{1}{g_o} \int_o^z g_{(z)}\, dz, \tag{3}$$

where

h = potential height above planetary surface (in cm),

Φ_z = gravitational potential at altitude z (in erg $gm^{-1} = cm^2\ sec^{-2}$), and

g_o = gravitational acceleration at zero altitude (constant for a specific latitude).

If empirical data on the distribution of g_o with planetary latitude on a non-spherical, rotating planet are available, the true planetary radius at a given latitude can be replaced by an "effective planetary radius," so that

$$g_{(z)} \approx g_o \frac{R_o^2}{(R_o + z)^2}, \tag{4}$$

where R_o = effective planetary radius at a specific latitude; thus, g_o as well as $g_{(z)}$ are valid at this chosen latitude. This is successful on Earth[21] and yields, for the gravitational acceleration at great altitudes over specific latitudes, numerical values that are as accurate as approximations based on the expansion of the gravitational potential in infinite series of spherical harmonics with empirical values of the second harmonic coefficient.[16] Lacking empirical data for the latitude dependence of g_o on Mars, we chose the following planetary radii to reflect upper and lower probable limits and a probable standard condition:

Table 2

PRINCIPLE PLANETARY PARAMETERS

Symbol	Parameter	Units	Lower Limit	Tentative Standard	Upper Limit
R_o	Effective planetary radius	cm	3440×10^5	3375×10^5	3322×10^5
g_o	Effective surface acceleration of gravity	cm sec^{-2}	360	375	390
M	Representative planetary mass	gm	6.389×10^{26}	6.406×10^{26}	6.455×10^{26}

Note that the values for planetary masses are illustrative only, and would not necessarily represent the non-rotating inertial mass.

Using "effective planetary radius" to account for flattening and rotation of Mars, we can integrate Eq. (3) to yield

$$z = \frac{R_o h}{R_o - h} \qquad \text{or} \qquad h = \frac{R_o z}{R_o + z} \quad . \tag{5}$$

The resulting potential height h (in cm) will be an artificial measure (particular to Mars) of the increase of gravitational potential and the decrease of gravitational acceleration with altitude for a specific latitude.

APPARENT GRAVITATIONAL FIELD

If the physical characteristics of a planet are known with higher accuracy, the concept of potential height can be further expanded to represent the forces acting at different latitudes upon an atmosphere rotating with the planet. In Eq. (3), the approximate expressions for the gravitational potential and its gradient become:

$$\Phi_{(z,\varphi)} = \frac{GM}{r}\left[1 + \frac{J_2}{2}\frac{R_e^2}{r^2}(1 - 3\sin^2\varphi)\right] + \frac{\Omega^2}{2} r^2 \cos^2\varphi \ , \tag{6}$$

where

$$g_{(z,\varphi)} = - \frac{\partial \Phi}{\partial r} , \tag{7}$$

and

$$r = R_e \; (1 - f \sin^2 \varphi) + z , \tag{8}$$

where

r = radius vector,
G = universal gravitational constant,
M = planetary mass,
R_e = equatorial radius,
J_2 = second harmonic coefficient,
Ω = angular rotation,
φ = planetary latitude, and
f = flattening.

It is evident that with these input quantities, the computer program becomes generally applicable to any planet. This routine was used to compare results at different latitudes at higher altitudes (see Appendix F). Within the still existing uncertainties of the physical characteristics of Mars, both routines are obviously more accurate than input data warrant.

MOLECULAR SCALE TEMPERATURE

Since the mean molecular weight is also a function of altitude, a second substitution is necessary, defining a "Molecular Scale Temperature" T_m as

$$T_m = \frac{m_o}{m} T , \tag{9}$$

where

m_o = mean molecular mass at zero altitude = constant,
m = f(z) or f(h),
T_m = f(z) or f(h), and
T = f(z) or f(h).

With the substitutions of molecular scale temperature and potential height, Eq. (2) becomes

$$dp = - g_o \; \rho \; dh . \tag{10}$$

With the help of Eqs. (1) and (9), it can be integrated with certain restrictions on the variations of molecular mass and kinetic temperature with altitude, yielding

$$P_{(h2)} = P_{(h1)}\, e^{-\frac{g_o m_o}{R^*} \int_{h_1}^{h_2} \frac{dh}{T_m}} \tag{11}$$

Specifically, if the variation of molecular scale temperature with potential height is either zero or constant in a certain height interval, that is, where

$$d\,T_m = Ldh \quad , \tag{12}$$

but where

$$L \equiv \frac{\partial T_m}{\partial h} \quad \text{with} \quad \frac{\partial^2 T_m}{\partial h} \equiv 0,$$

then (for L = constant):

$$P_{(h_2)} = P_{(h_1)} \left(\frac{T_{m(h_1)}}{T_{m(h_1)} + L(h_2-h_1)} \right)^{\frac{m_o g_o}{R^* L}} \quad ; \tag{13}$$

for $L = 0$ (i.e., T_m = constant between h_1 and h_2):

$$P_{(h_2)} = P_{(h_1)}\, e^{-\frac{m_o g_o}{R^* T_m}(h_2-h_1)} \quad . \tag{14}$$

It is now possible to evaluate Eq. (1) at all levels of h and z, and to derive mass densities ρ for given values of the ratio T/m. In addition, any combination of known and unknown parameters in Eq. (9) will specify what assumptions must be made about the missing information.

The computing program allows flexibility with respect to acceptance of known parameters and conditions inherent in Eqs. (1), (3), (5), (9), and (11) as limited by conditions in Eq. (12), and can be called upon to provide output of additional quantities, such as scale heights, columnar mass, number densit and other auxiliary quantities. As described in the

following sections, uncertainties in a variety of parameters for Mars necessitated the employment of maximization and iteration techniques to develop a series of self-consistent model atmospheres, representative of limiting conditions in various altitude intervals.

Appendix B

LOWER ATMOSPHERE

An earlier study[4] calculated realistic upper and lower limits for the permissible ranges of temperature, pressure, and density of the Martian atmosphere at altitudes below the then-unknown mesopause. It documented in detail published justifications for the required choices among available physical data. The present work extends these limits upwards, following (with one exception) the procedures of another, earlier study.[1]

The exception is a result of uncertain values of Martian mass, diameter, and flattening, leading to further uncertainties about the precise variation of gravitational acceleration with altitude. For variation in the gravitational potential cannot be neglected at altitudes above some 150 km without introducing appreciable errors. In order to achieve the necessary precision, the numerical integrations were performed in terms of "potential height" and effective planetary radius, or indirectly in terms of apparent gravitational potential, as the previous section explained. But for this one exception, the tentative model atmospheres correspond below 150 km to limiting envelopes published earlier, and the same meteorological situations apply as discussed there.[4]

Table 3

BASIS OF LOWER ATMOSPHERIC DATA

Present Work	Earlier Work (with Reference)
Tentative Minimum	Model II Lower Limit[4] Lower Limit Model (Engineering Atmosphere)[1]
Tentative Standard	Model II Mean[4]
Tentative Maximum	Upper Limit Model (Engineering Atmosphere)[1]

Appendix C

MESOPAUSE

Chamberlain[11] locates the Martian mesopause where the conductive heat flux is about 0.07 ergs/cm^2 sec, the number density is 1.2×10^{14} cm^{-3}, and the temperature approximately 76°K. Based on the model atmosphere of Goody[23] for heights up to 100 km, and an adiabatic temperature decrease above 114 km, he obtains a mesopause altitude of about 130 km for these conditions.

From Chamberlain's data of mesopause temperature and number density, we can determine the amount of columnar mass penetrated down to this level as between 3.23×10^{-3} gm/cm^2 and 3.77×10^{-3} gm/cm^2, depending on assumptions about the thermospheric molecular composition and the decrease of gravitational acceleration with altitude. This condition corresponds to a pressure level of about 1.259×10^{-3} mb.

We now find the altitude where this condition is valid for the upper and lower limits of our engineering model atmosphere,[1] by extrapolating its upper limit from 150 km for an adiabatic distribution, and the lower limit for an isothermal temperature structure, respectively.

As expected, the mesopause lies at a rather low altitude for the lower limit of the engineering model atmosphere, and a very high altitude for the upper limit, thus bracketing Chamberlain's determination. However, it can be noted that the temperature is almost the same in both limiting cases, as required by the physics of the situation. This result allows us to reduce the probable limits for extreme conditions in the upper atmosphere of Mars considerably beyond any straight extrapolation of the engineering model atmosphere.

In addition, we can determine the extreme altitude ranges for certain characteristic processes. Of special interest to an understanding of the physical state of a planetary atmosphere are the levels of vibrational and rotational relaxation, as defined by Curtis and Goody.[24] Similarly, we can now estimate the

approximate altitudes where solar radiation pressure equals atmospheric drag on a satellite of representative dimension, or where the continuum aerodynamic regime changes to free-molecular flow. These levels are summarized in Table 4.

It was pointed out originally(4) that the lower limit of our model atmosphere was relevant for a very cold region on Mars with low surface temperatures, a cold troposphere and mesosphere, and the smallest probable total of air mass. In such an atmosphere, the mesopause will be as low as 89 km, and the temperature will begin to increase upwards from there on.

In contrast, the upper limit pertained to a planet or area with high surface temperatures and an efficiently warmed mesosphere. As a result, however, the cold mesopause level will be as high as 202 km and heating due to absorption of far-ultraviolet solar radiation will take place only at higher altitudes.

In order to provide also a tentative standard atmosphere, the Model II Mean of Ref. 4 was extended upwards isothermally, resulting in an intermediate mesopause altitude of 144 km.

Table 4

ALTITUDE LEVELS OF CHARACTERISTIC PHENOMENA

Phenomenon	Tentative Minimum		Tentative Standard		Tentative Maximum	
	Altitude (km)	Density (gm cm^{-3})	Altitude (km)	Density (gm cm^{-3})	Altitude (km)	Density (gm cm^{-3})
Tropopause	26	1.4×10^{-5}	30	2.5×10^{-5}	10	1.1×10^{-4}
Vibrational Relaxation (CO_2)	68	8.0×10^{-8}	112	4.8×10^{-8}	141	2.6×10^{-7}
CO_2 Dissociation	82	1.4×10^{-8}	127	1.5×10^{-8}	201	1.5×10^{-8}
Mesopause	91	4.5×10^{-9}	150	2.6×10^{-9}	215	4.4×10^{-9}
Free Molecule Flow	218	8.6×10^{-13}	368	8.5×10^{-13}	450	7.0×10^{-13}
Rotational Relaxation	273	1.5×10^{-13}	555	7.2×10^{-14}	895	3.4×10^{-14}
Escape Level	594	8.1×10^{-16}	1540	2.6×10^{-16}	>2800	
	635	5.3×10^{-16}	1763	1.3×10^{-16}		
Radiation Pressure Equal Drag	825	1.0×10^{-16}	1860	1.0×10^{-16}	≈3000	

Appendix D

THERMOSPHERE

Although we have now arrived at extreme probable limits for the altitude and temperature of the mesopause on Mars, we still need to know the precise absorption characteristics of the thermosphere to determine the rate of temperature increase with altitude above this level. As Chamberlain[11] points out, the initial temperature-altitude gradient could be as high as 20°/km, if the upper atmosphere of Mars had the same chemical composition as that of Earth. He finds, though, that CO in the Martian upper atmosphere will act as an effective thermostat, reducing this gradient substantially. His resultant temperature distribution is achieved through an iterative process; we shall assume that his assumptions are valid.

Nicolet, in his studies of the upper atmosphere of Earth,[19] has shown that the vertical distribution of density at very high altitudes (above the thermopause) depends critically on the temperature at the mesopause and above. But with diffusion playing the dominant role, the variation of the scale height gradient in the thermosphere is due essentially to a decrease in molecular mass, rather than to an increase of the kinetic temperature.

We are then faced with the problem of locating the thermopause and the critical level of escape. This escape level will be reached at an altitude where the mean free path becomes equal to the pressure scale height. The mean free path itself is a function of the particle density and the effective collision diameter (σ) of the particles involved. Where dissociation takes place, the mean molecular mass and the mean effective collision diameter will tend to decrease from the value of about 3.6×10^{-8} cm for a mixture of nitrogen, oxygen, and carbon dioxide molecules. Ionization will tend to increase the effective collision diameter, however, and we are probably justified in retaining a value of $\sigma = 3.5 \times 10^{-8}$ cm throughout the Martian thermosphere.

Chamberlain gives a value of $n = 1 \times 10^7$ and $T = 1100^\circ K$ for the level of escape at an altitude of 1500 km; this corresponds to a pressure of about 1.5×10^{-9} mb.

From the relation

$$\lambda^* = \frac{1}{\sqrt{2}\,\pi\,\sigma^2\,n^*} = H^* = \frac{p^*}{\rho^* g^*} ,$$

where

λ^* = mean free path at level of escape,
σ = mean effective collision diameter of air molecules,
n^* = particle density at level of escape,
H^* = pressure scale height at level of escape,
ρ^* = mass density at level of escape,
p^* = pressure at level of escape,
g^* = gravitational acceleration at level of escape,
m^* = mean molecular mass at level of escape,
T_m^* = molecular scale temperature at level of escape, and
T^* = true kinetic temperature at level of escape,

it follows that the atmospheric pressure p^* at the escape level will be given by:

$$p^* = \frac{m^* g^*}{\sigma^2} \times 3.7316 \times 10^{-25} \text{ [dynes/cm}^2\text{]},$$

and the atmospheric temperature T^* by:

$$\frac{T_m^*}{m_o} = \frac{T^*}{m^*} = \frac{m^* g^*}{n^* \sigma^2} \times 2.7035 \times 10^{-9} \text{ [}^\circ\text{K]}.$$

Depending on assumptions about the value of the gravitational acceleration at the surface and the planetary radius, Chamberlain's escape-level values apparently correspond to

$$2.2 \times 10^{16} < \frac{m}{\sigma^2} < 2.3 \times 10^{16} \text{ [cm}^{-2}\text{]},$$

or effective collision diameters between 2.6 x 10^{-8} cm and 2.8 x 10^{-8} cm for mean molecular masses of 16 to 17.

In studies of the upper atmosphere of Earth, satellite-drag observations lead to values of mass density ρ, and rocket-absorption measurements to the knowledge of number density n. But these can be interpreted only in terms of pressure and kinetic temperature, if the mean molecular mass is known. Similarly, even if the thermal heat flux through the Martian exosphere is assumed to be known, as determined by Chamberlain, a singular solution in terms of a consistent model atmosphere will still be incomplete, as is discussed in Appendix A.

For our purpose of arriving at reasonable probable limits of pressure and density in the upper atmosphere of Mars, a series of model atmospheres was therefore computed from different basic assumptions. This flexible approach allowed for our ignorance of the precise variation with altitude of the mean molecular mass for the physical conditions inherent in different starting conditions near the planetary surface.

The problem of integration can be summarized as follows:

We assume that atmospheric conditions are known and specified at the level of the mesopause. We further assume that either the true kinetic temperature in the thermosphere above the level of escape is known, or that the molecular scale temperature can be estimated. As Chamberlain discusses in detail,[11] however, only an iterative process will yield the altitude distribution of the specific molecular and atomic constituents, and this only for an assumed relative preponderance of constituents, with assumptions about their absorbing efficiencies and the resultant heat flux. On the other hand, since we are primarily interested in the distribution of mass density and pressure with altitude, it is feasible to integrate the atmospheric equations in terms of molecular scale temperature, regardless of the true kinetic temperature at levels between.

Conversely, an assumption must be made about the most likely distribution of mean molecular mass m with altitude. But the

possible errors thus introduced in terms of pressures and mass densities are of the order of factors of 2 or possibly of 3 rather than orders of magnitude. Figure 4 shows this schematically.

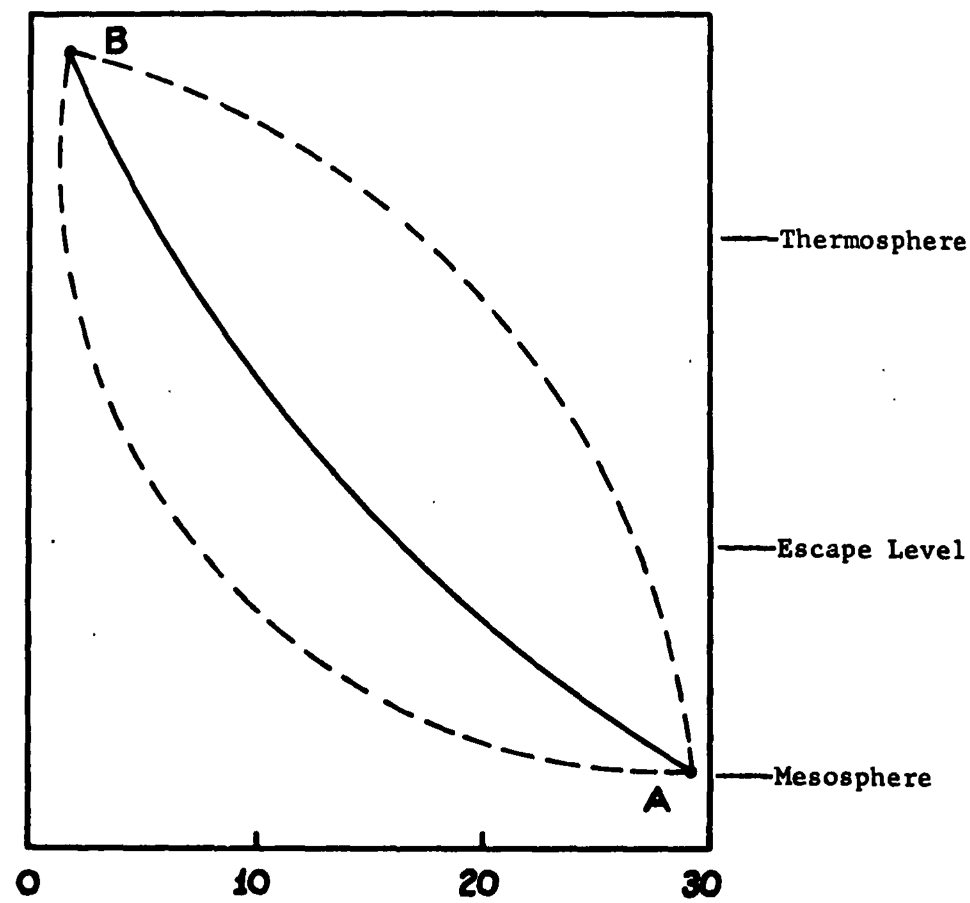

Fig. 4 — Schematic sketch of variation of mean molecular mass with altitude

At the mesopause level, m will be near 30 (Point A). Somewhere high in the thermosphere where, for all practical purposes, outer space is approached, m might be as low as 4 (Point B). In such a highly ionized fringe region, m is complicated by an orbiting component of particles, electrons, and the flux of escaping lighter elements. The true altitude distribution of m,

governed by diffusive separation in the gravitational field, may lie somewhere between the dashed lines. But any reasonable integration path from A to B for a specific energy flux, i.e., temperature equilibrium, will be unlikely to deviate from the true molecular mass at any level by more than a factor of 3.

From a set of plausible model atmospheres over various integration paths, we finally selected three that represented the limiting probable conditions in terms of density and pressure distribution. In the next section, Table 6 lists the precise construction parameters calculated from the following primary considerations.

TENTATIVE MINIMUM

It was assumed that, for this extreme case, minimum heating and dissociation takes place in the thermosphere and that in the exosphere the conditions were equivalent to a kinetic temperature of 906°K, as suggested recently by Walker and Jastrow,[25] combined with a molecular mass of 17. The slow decrease from a molecular mass of 30 (below the escape level) to 17 (near 2600 km altitude) was assumed to be due to dissociation of both oxygen, nitrogen, and CO_2.

TENTATIVE MAXIMUM

Maximum heating was assumed to occur in the thermosphere, reaching exponentially a kinetic temperature of 1100°K near 500 km altitude with a molecular mass of 22, corresponding to an even mixture of nitrogen molecules and oxygen atoms. In the exosphere, at a potential height of 1500 km (equivalent to a geometric altitude of 2735 km), it was assumed that the molecular scale-temperature reached 4400°. If the kinetic temperature remained constant at 1100° K up to these altitudes, there would be a molecular mass of 7 — a mixture primarily of atomic nitrogen and a flux of atomic oxygen and helium escaping through the thermosphere and exosphere.

As was explained earlier, however, this molecular scale-temperature of 4400°K is also equivalent to any combination of

$$T_m = 4400^\circ = \frac{m_o}{m} T$$

at this altitude, ranging from an implausible kinetic temperature of 4400° with no dissociation, to an equally implausible 314°K in a hydrogen atmosphere. Reality certainly lies somewhere in between. The technique's advantage is this ability to provide reasonably correct values of pressure and mass density without precise knowledge of the kinetic temperature distribution and, separately, the mean molecular mass.

TENTATIVE STANDARD

A rather high kinetic temperature of 162.5°K was derived from an extension of the Model II Mean Atmosphere[4] for the mesopause at an altitude of 144 km. Independently, Walker and Jastrow have recently published a mesopause temperature for Mars (altitude unknown) of 176°K.[25] From this level, the kinetic temperature was assumed to increase, reaching 1000°K at 500 km altitude with a slight decrease of mean molecular mass. The escape level is reached between 1540 km and 1760 km, and the kinetic temperature was assumed to remain constant at 1100°K from 1500 km to 2800 km, with the molecular mass decreasing from 16 (near the escape level) to 14 (at about 2800 km).

Any of these assumptions for probable limiting conditions would appear equally reasonable on the basis of Chamberlain's investigation of the probable mechanisms responsible for the thermal behavior of the Martian upper atmosphere. But to determine the limiting parametric envelopes, the specific numerical choices are expected to represent also realistic assessments of the possible variability. This will also roughly account for the expectation,

based on knowledge of the Earth's upper atmosphere,[8] that the night temperature at the thermopause and in the thermosphere will be substantially lower than day temperatures.

Appendix E

CONSTRUCTION PARAMETERS

Figures 1, 2, 3, and Table 1 show the final numerical results as the three tentative model atmospheres. Actual conditions at any altitude level should fall between the tabulated value given by the Tentative Maximum and that given by the Tentative Minimum. It must be emphasized, however, that the atmospheric parameters are tabulated to three or four significant figures for mathematical convenience only. The spread in values between Maximum and Minimum indicates the uncertainty at any altitude and, if wished, can be interpreted as the probable error of the Tentative Standard Atmosphere.

Table 5 lists the principal construction parameters used in the computational program, and some pertinent data for different altitude levels of special interest. The reason for the choice of certain input parameters pertaining to the lower atmosphere, and planetary parameters, has been explicitly discussed in an earlier publication.[4]

Table 6 provides information about the thermal structure of the model atmosphere in terms of molecular scale temperature and potential height. For illustrative purposes, it also shows one possible choice of the combined variation of kinetic temperature and molecular mass for the given molecular scale structure.

Table 5

CONSTRUCTION PARAMETERS

Parameters	Units	Model Atmosphere		
		Tentative Minimum	Tentative Standard	Tentative Maximum
PLANETARY CONSTANTS				
*Effective planetary radius	km	3440	3375	3322
*Effective surface acceleration of gravity	cm sec^{-2}	360	375	390
SURFACE REGION				
*Atmospheric pressure	mb	41.04	85	132.6
Atmospheric density	gm cm^{-3}	7.404×10^{-5}	1.186×10^{-4}	1.489×10^{-4}
*Atmospheric temperature	^{o}K	200	250	300
*Mean molecular mass		30	29	28
Scale height	km	15.4	19.1	22.8
Number density	cm^{-3}	1.487×10^{18}	2.463×10^{18}	3.20×10^{18}

Table 5 (Continued)

Parameters	Units	Model Atmosphere: Tentative Minimum	Tentative Standard	Tentative Maximum
		TROPOPAUSE		
Geometric altitude	km	26.198	30.269	10.030
*Potential height	km	26.000	30.000	10.000
Acceleration of gravity	cm sec^{-2}	354.579	368.363	387.656
Atmospheric temperature	^{o}K	101.46	162.5	262.86
		OZONOPAUSE		
Geometric altitude	km	none	none	61.1—135.3
*Potential height	km			60.0—100.0
		MESOPAUSE		
Geometric altitude	km	91.364	150.418	215.078
Potential height	km	89.000	144.000	202.000
Acceleration of gravity	cm sec^{-2}	341.613	343.683	344.013

Table 5 (Continued)

Parameters	Units	Model Atmosphere		
		Tentative Minimum	Tentative Standard	Tentative Maximum
MESOPAUSE (continued)				
*Pressure	mb	1.2595×10^{-3}	1.226×10^{-3}	1.107×10^{-3}
Mass density	$gm\ cm^{-3}$	4.479×10^{-9}	2.632×10^{-9}	4.387×10^{-9}
Number density	cm^{-3}	8.99×10^{13}	5.468×10^{13}	9.438×10^{13}
Kinetic temperature	^{o}K	101.46	162.5	84.96
Mean molecular mass		30	29	28
Columnar mass	$gm\ cm^{-2}$	3.687×10^{-3}	3.568×10^{-3}	3.217×10^{-3}
Scale height	km	8.23	13.56	7.33
REFERENCE LEVEL ONE				
*Geometric altitude	km	500.000	500.680	500.000
Potential height	km	436.548	436.000	434.589
Gravitational acceleration	$cm\ sec^{-2}$	274.427	284.369	294.634
Pressure	mb	5.819×10^{-9}	3.719×10^{-7}	1.649×10^{-6}

Table 5 (Continued)

Parameters	Units	Model Atmosphere		
		Tentative Minimum	Tentative Standard	Tentative Maximum
	REFERENCE LEVEL ONE (continued)			
Mass density	gm cm^{-3}	2.317×10^{-15}	1.252×10^{-13}	3.967×10^{-13}
*Molecular scale temperature	^{o}K	906	1035.7	1400
	REFERENCE LEVEL TWO			
*Geometric altitude	km	1500.000	1500.037	1502.531
Potential height	km	1044.534	1038.000	1034.589
Gravitational acceleration	cm sec^{-2}	174.568	179.805	184.907
Pressure	mb	8.974×10^{-12}	1.709×10^{-9}	4.110×10^{-8}
Mass density	gm cm^{-3}	2.025×10^{-18}	2.990×10^{-16}	4.480×10^{-15}
*Molecular scale temperature	^{o}K	1598.8	1993.45	3089.49

Table 5 (Continued)

Parameters	Units	Model Atmosphere		
		Tentative Minimum	Tentative Standard	Tentative Maximum
	REFERENCE LEVEL THREE			
Geometric altitude	km	2659.794	2700.000	2734.907
Potential height	km	1500.000	1500.000	1500.000
Gravitational acceleration	cm sec^{-2}	114.496	115.740	117.317
Pressure	mb	2.218×10^{-13}	1.005×10^{-10}	7.898×10^{-9}
Mass density	gm cm^{-3}	5.005×10^{-20}	1.539×10^{-17}	6.045×10^{-16}
*Molecular scale temperature	^{o}K	1598.8	2278.57	4400

*indicates program input data

Table 6

THERMAL STRUCTURE OF MODEL ATMOSPHERES

Potential Height (km)	Molecular Scale Temperature (^{o}K)	Gradient of Molecular Scale Temperature (^{o}K/km)	Representative Kinetic Temperature (^{o}K)	Representative Mean Molecular Mass
		TENTATIVE MINIMUM		
0	200		200	30
		-3.79		
26	101.46		101.5	30
		0		
89	101.46		101.5	30
		+2.315		
436.655	906		906	30
		+1.140		
1044.534	1599		906	17
		0		
1500.0	1599		906	17
		TENTATIVE STANDARD		
0	250		250	29
		-3.75		
10	212.5		212.5	29
		-2.5		
30	162.5		162.5	29
		0		
144	162.5		162.5	29
		+2.99		
436	1035.714		1000.0	28
		+1.59		
1038	1993.749		1100.00	16
		+0.62		
1500	2278.569		1100.00	14
		TENTATIVE MAXIMUM		
0	300		300	28
		-3.714		
10	262.86		263	28
		0		
60	262.86		263	28
		+0.51		
70	267.96		268	28
		+1.1		
100	300.96		301	28
		0		
130	300.96		301	28
		-3.0		
202	849.6		850	28
		+5.65		
434.589	1400.0		1100	22
		+2.82		
1500	4400.0		{1100 2200	7} 14

Appendix F

EXOSPHERE

The validity of the equations, collected in Appendix A, becomes extremely doubtful in the higher regions of the exosphere. Without a magnetic field, the radial extent of any planetary exosphere, rotating with the planet, has for its absolute outer limit the distance at which gravitational and centrifugal forces balance. This occurs at about 35,800 km above the Earth's equator, and at about 17,000 km above Mars'. Long before this, however, the particle density of the Martian exosphere will have decreased to that of interplanetary space. This is evident from studies of the probable exospheric regimes on Earth published by Grimminger,[26] Milne,[27] Öpik and Singer,[28] Shen,[29] and others.

Nevertheless, the previously discussed computer equations permit the extention of numerical integration, with assumptions about the radial distribution of mean molecular mass, up to altitudes in excess of one planetary diameter. While no great reliability can be assigned to the numerical results, exospheric density data thus obtained appear to fall between values derived by Shen[29] for a collisionless exosphere, and a barometric formula distribution, with constant kinetic temperature or molecular mass, respectively. The results indicate the relative importance of absorption of solar radiation by different molecular and atomic species, even though they are quantitatively inconclusive as regards the actual radial extent of the Martian exosphere.

For a special case, however, of the distribution of atmospheric mass density in the equatorial plane, the calculated upper and lower possible extreme limits indicate that Phobos may conceivably be subject to some extremely small drag effects. Work on this problem is in process.

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